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An Explanation of Tektite Chemistry in Terms of Lunar Ash Flows

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Abstract

The variation of SiO_2 among tektites and allied materials suggests that they have passed through a stage of mechanical sorting, similar to the sorting of sediments into silts and sandstones. The sorting was apparently not done by water, in view of the dryness of tektites. It is suggested that it was done by a lunar ash flow.

Theoretical calculations of pressure, temperature, and voidage (fraction of the volume not occupied by solid matter) are made for the dense phase (bulk density 0.5 to 1.0 gm/cm³) of an ash flow, assuming a steady state, uniform temperature, and steady emission of gas from the solid matter. The problem reduces to an ordinary non-linear differential equation of the first order; the solution is presented in non-dimensional variables, together with homology relationships for the physical parameters. For a constant model, the required gas emissivity is found to vary inversely with the square of the gravity.

Above the dense phase, there may be a dilute phase consisting of gas with suspended particles, having a bulk density of 0.12 gm/cm³ or less. The dilute phase is relatively unimportant in terrestrial flows; but in a lunar ash flow it is likely to be the predominant mode of transport. It is found to be an isothermal pseudo-gas, with a scale height on the moon of a few hundred meters.

This concept will explain the evidence of sorting. It is also consistent with the fairy-castle structure of the surface, the petrography of the Muong Nong tektites, and the morphology of the maria.

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1. Introduction

In a series of geochemical studies, S. R. Taylor and his co-workers [Cherry, Taylor and Sachs, 1960; Cherry and Taylor, 1961; Taylor, Sachs and Cherry, 1961; Taylor and Sachs, 1962; Taylor and Sachs, 1964; Taylor and Solomon, 1964] have brought forward evidence that the silica content of tektites varies independently of the other constituents. They have shown a remarkable geochemical coherence between elements which, in most rocks, vary independently or in opposite directions, such as magnesium and sodium. They find that the chemistry of tektites, apart from the content of water and volatiles, can be described as a mixture, in varying proportions, of some sort of intermediate rock, such as a shale, with pure SiO_2 . Although the mixture falls in the same range of silica content as acid igneous rocks, like granites or rhyolites, they find that there are decisive differences in composition. Although their work is the most thorough from this point of view, the essential idea is not new; and in fact very similar opinions were voiced earlier by Mueller [1915], Loewensohn-Lessing [1935], Barnes [1939], and others. The essential difference in the major elements is that tektites are richer in alkaline earths and iron, especially ferrous iron, than granites; and they are poorer in alkalis. Taylor follows the opinion first voiced by Barnes to the effect that these peculiarities make tektites resemble sedimentary rocks.

Barnes [1956], considering much the same evidence, but also considering the aerodynamic evidence of external origin, once proposed that tektites should be regarded as sedimentary rocks from some non-terrestrial source.

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This idea has not received the attention which it merits; and in fact was abandoned by Barnes himself. The present paper is devoted to a mathematical study of one version of this hypothesis. There are several important facts which let us elaborate Barnes's hypothesis further:

a. The extraterrestrial source in question must be the moon, even though Barnes postulated an earth-size planet with atmosphere and ocean. The absence of cosmogenic isotopes such as Al^{26} and Be^{10} [Viste and Anders, 1962] strongly suggests an origin in the near vicinity of the earth. A further argument of the same kind follows from Urey's [1957] discussion of the tektite strewnfields. Urey pointed out that a group of bodies arriving from an extraterrestrial source ought to fall either in a world-wide pattern, like a typical meteor shower, or in a local pattern on the order of ten kilometers or less in dimensions, if it resulted from breakup in the atmosphere, as in the case of numerous meteorite falls. The observed tektite patterns are too large for normal atmospheric breakup, and too small for the kind of breakup in interplanetary space which seems to have produced the meteor showers. Relying on some nineteenth century work by Roche [Tisserand, 1896], Urey pointed out that this difficulty had its roots in the tidal effects of the sun, which would dissipate any reasonable shoal of tektites. To answer this objection, it was found necessary [O'Keefe, 1961; O'Keefe and Shute, 1961] to appeal to the idea that the tektites had been in orbit around the earth before they fell;

in this case the orbits of the Cyrillids or of the sustainer of Col. Glenn's capsule [O'Keefe, 1964] constitute examples of bodies which fell, or at least appeared in the atmosphere in patterns which were neither local nor world-wide. But a body coming from the moon is far more likely to get into orbit around the earth than one which is somehow captured from interplanetary space. Again, the chemical resemblance between tektites and the crust of the earth is considerably closer than between tektites and meteorites or the sun. For all these reasons, the moon is the most likely source for tektites if they are assumed to come from some place other than the earth.

In the second place, we note that the chief agent responsible for giving sedimentary rocks their characteristic chemistry is the effect of transportation by a fluid [Pettijohn, 1957]. It is the fact that sand grains are coarser than particles of silt or clay which causes them to be separated by water or air, and thus to form the beds of shale and sandstone, or sand dunes and loess which result in the distinctive chemistry of sedimentary rocks. Thus the hypothesis of sedimentary origin outside the earth implies that on this extraterrestrial body there exists some fluid capable of transporting rock fragments.

If we are to think in terms of the moon, then there is only one fluid logically capable of sorting rock fragments; and this is the gas which is, from time to time, expelled from some lunar craters [Kozyrev, 1958; Greenacre, 1963]. Liquid water cannot now exist on the moon's surface because of the low pressure; and even if it had existed at a time near the formation of the moon, this would not provide a solution

for our problem, since, as Tilton [1958] (using lead, uranium and thorium), and Schnetzler and Pinson [1963] (using rubidium and strontium) have pointed out, the tektite material was differentiated from a more primitive magma only a few tenths of an aeon ago. Moreover, one of the most remarkable properties of tektites is their extraordinary dryness [Friedman, 1963]; they have thousands of times less water than a typical sedimentary rock. As the experience of the glass-making industry since 800 B.C. shows, it is necessarily a long process to rid a normal rock of its water content. Hence we may suppose with some confidence that the transporting agent was a gas; and if the origin was the moon, it must have been a temporary flow of gas, since the moon's surface normally has less than 10^{-13} atmospheres.

T. Gold [1955] proposed that the maria should be considered as fluidized dust produced by weathering and erosion in the highland areas of the moon and transported to the lowlands by some mechanism such as an evaporation reaction, micrometeorite shock, or periodic electrostatic charging. This mechanism cannot furnish an explanation of the tektites, however, since it would not be expected to change the Rb-Sr ratio, which would then presumably correspond to ages of a few billion years.

A plausible mechanism for the emplacement of tektite material appears to be the ash flow process. On the earth, finely divided particles of partially solidified lava, called volcanic ash, may be emplaced either by passage through the air, as in a normal ash fall of the Vesuvian type, or by the mechanism of the ash flow, in which the mixture of ash and upward flowing gas constitutes what is called in

industry a fluidized bed. The bed behaves, in many respects, like a fluid of low viscosity; there are other reasons [Cameron, 1964] for thinking that it may play a significant part in shaping the lunar surface. In the next two sections, we shall attempt to work out a physical theory of ash flows. Such a theory has not yet been worked out even for terrestrial flows, partly because it was not until the last twenty years that there was either the motive, in the form of recognition of the great extent of ash flows, or the opportunity, in the form of a physical theory of fluidization.

2. Fluidization and ash flows, general.

Fluidization [Leva, 1959] is a physical process by which particles of solid matter are suspended in a fluid by the motion of the latter. A cushion is provided between the solid particles so that the mixture behaves like a fluid of relatively low viscosity. A fluidized bed differs from an emulsion in the fact that it is only stable while the fluid is in motion; it normally involves much larger particles than an emulsion (from 100 microns to a centimeter or more). The fluid may be either a liquid or a gas; in the present paper we shall deal only with gases.

If sand is spread over an air filter in a box, and gas is passed through from underneath, there is at first no disturbance of the sand. This phase is called the fixed bed. As the gas flux, measured in gm/cm^2 sec is increased, there comes a value G_{mf} , called the flow for minimum fluidization, at which the character of the mass changes abruptly to a pseudo-fluid, in which waves can be set up, which will float light objects, and which tends to form a level surface. At this point we have

the dense phase of the fluidized bed. Ordinarily the overall density of the mass has decreased only fractionally--say 10 to 50 percent, as compared with the fixed bed.

If the flux is increased, the flow is seen to become irregular; bubbles of gas rise through the bed and burst. This process is called slugging. If the flow of gas is further increased, there results an extremely disturbed and irregular regime, which terminates when the flow becomes so rapid as to carry off the sand grains. The latter point is reached when the velocity of the gas at the surface of the bed becomes greater than the order of magnitude of the rate of fall of the sand grains under Stokes' Law. Beyond this point is a regime which is called the dilute phase; the solid matter now occupies less than 5% of the total volume, and it is no longer stationary, but is carried along with the gas flow.

In calculating the properties of an ash flow, the voidage, or fraction of the mass which is not occupied by solid matter, is of primary importance. For the fixed bed, the voidage may be as much as 40% if the particles are spiny or irregular, as with volcanic shards (particles of ash). At minimum fluidization, the voidage is likely to be near 60%; and at the upper limit of the dense phase, the voidage is from 75% to 80%. In the dilute phase, the voidage is, as mentioned, 95% or more. Between 80% and 95% no experimental studies have been successful in describing the properties of the gas-fluidized bed; in our discussion we will assume that the dense phase ends at a surface with 80% voidage, above which is the dilute phase.

Ash flows are, then, a geophysical application of the process of fluidization. Geologists have not distinguished between the two types of fluidization, since the terminology postdates the earlier geological studies. It appears, however, that both kinds occur; on the earth, the dilute phase is, we suspect, exemplified by the classic outburst of Mont Pelée [Lacroix, 1904]; the dense phase is then exemplified by the great "sand flow" (to use the obsolete term) which formed the Valley of Ten Thousand Smokes [Griggs, 1921].

3. Mechanics of ash flows: the dense phase.

A full discussion of the mechanics of an ash flow would involve 12 simultaneous partial differential equations, or 9 if it is restricted to 2 dimensions. In addition to the difficulty of solving them for any particular case, there is the important difficulty of gaining any understanding of ash flows as phenomena from the great variety of solutions which these equations would yield, depending on the boundary conditions. In the present paper, therefore, the attempt is made rather to study what is going on at a typical point in an ash flow in which the ash has no vertical motion. Several important simplifying assumptions are made.

First, it is assumed that the mass is all at the same temperature. So far as the solid particles are assumed, this assumption is justified by the observed fact that the cooling of an ash flow is a conspicuously slow process, even on the earth. In the center of an ash flow, it is common to find that the material remained hot and plastic so long that it welded the separate ash particles into a single mass; such bodies are

called welded tuffs. On the moon, the low thermal conductivity of the outer layers is such that the surface is able to maintain a temperature difference of 100° Centigrade between points a few centimeters apart during the whole lunar day (a fortnight). Thus the cooling of the solid matter will be very slow. Since the total mass of gas is not likely to exceed 1% of the solid matter, and since it is in intimate contact with the finely divided solid, it is clear that the gas will also maintain a uniform temperature throughout the period of a day or so while the flow is occurring.

Second, it is assumed that the solid matter does not move. It is not implied that there is no motion of the individual particles, of a random kind, but rather that there is no bulk upward or lateral motion of the mass, such as to change the bulk density, for example. The particles are, however, outgassing steadily.

With these assumptions, we first write the equation of hydrostatic equilibrium

$$(1) \quad \frac{dp}{dy} = -g (\rho_s + \rho)$$

where p is the pressure, the same for the gas as for the solid; g the acceleration of gravity; ρ the gas density, and ρ_s the bulk density of the solid. This equation simply asserts that the increase of pressure with depth is due to the increased weight of the vertical column above. If ρ_{oo} is the density of an individual solid particle, then

$$(2) \quad \rho_s = (1-\epsilon) \rho_{00}$$

where ϵ is the voidage.

In practice we shall neglect the gas density by comparison with that of the solids; the error is of the order of 1% at worst, and usually much less, especially on the moon.

We write the gas law as

$$(3) \quad \rho = \frac{m}{RT} p$$

where R is the universal gas constant, T the Kelvin temperature and m the molecular weight. We will treat $\frac{m}{RT}$ as a constant within any one flow. The gas is assumed to be predominantly steam.

Next is the equation of continuity for the gas. If we were considering merely the flow of gas through a wide pipe, we would have

$$(4) \quad \frac{d}{dy} (\rho v) = 0$$

where v is the gas velocity. This equation asserts that the number of grams per unit area and per unit time passing a given point is the same throughout the column under consideration. A similar equation holds in our case, even though the voidage changes, since v is the average flow, not the (undeterminable) velocity in a passage. Allowing for the emission of gas at a rate of q grams of gas per gram of solid matter

$$(5) \quad \frac{d}{dy} (\rho v) = q \rho_s ,$$

where q is assumed constant, because of the constancy of temperature.

Substituting for ρ_s from (1), we have, neglecting the gas density

$$(6) \quad \frac{d}{dy} (\rho v) = - \frac{q}{g} \frac{dp}{dy} .$$

Integrating over y from $y = 0$, where $p = p_0$ and $v = 0$.

$$\int_{y=0}^y \frac{d}{dy} (\rho v) = - \frac{q}{g} \int_{p_0}^p \frac{dp}{dy}$$

$$(7) \quad \rho v = \frac{q}{g} (p_0 - p).$$

The above equations are perhaps obvious; the next, and last, of the determining equations, (8), below, is less so. The flow of a gas through a porous medium obeys Darcy's Law

$$(8) \quad \frac{dp}{dy} = \frac{\mu v}{\lambda} - \rho g$$

in which λ is the porosity of the medium. Here ρg is again negligible by comparison with the first term. The porosity is implicitly given by the equation of Leva [1959, p. 48],

$$(9) \quad \frac{dp}{dy} = - \frac{200 v \mu}{D_p^2 \phi_s^2} \cdot \frac{(1-\epsilon)^2}{\epsilon^3},$$

where D_p is the particle diameter, ϕ_s a shape factor, which we here take to be 0.8. (Leva's equation also includes a factor g_c in the denominator which is unity if appropriate units are used in the English or the metric system.

We thus have 4 equations, namely (1), (3), (7), and (9) for the four unknowns ϵ , ρ , v and p . The bulk density of the solids, ρ_s , is related to the voidage by the trivial equation (2).

To solve, we eliminate $\frac{dp}{dy}$ by comparing (1) and (9), neglecting the gas pressure

$$(10) \quad g \rho_s = \frac{200 v \mu}{D_p^2 \phi_s^2} \cdot \frac{(1-\epsilon)^2}{\epsilon^3}$$

We substitute (3) in (7), and obtain

$$(11) \quad v \cdot \frac{m}{RT} \cdot \frac{g}{q} = \frac{p_0}{p} - 1$$

We solve (10) for v , and substitute this result in (11), remembering (2)

$$(12) \quad \frac{m}{RT} \cdot \frac{\rho_{00} g^2 D_p^2 \phi_s^2}{200 \mu q} \cdot \frac{\epsilon^3}{1-\epsilon} = \frac{p_0}{p} - 1.$$

Let

$$(13) \quad F = \frac{m}{RT} \cdot \frac{\rho_{00} g^2 D_p^2 \phi_s^2}{200\mu q},$$

and

$$(14) \quad \eta = \frac{\epsilon^3}{1-\epsilon}.$$

Then

$$(15) \quad F\eta = \frac{p}{p_0} - 1$$

In order to trace the variation of physical constituents along a column through the dense portion of the ash flow, we begin by assuming a base pressure p_0 . This is the pressure at the ground level underneath all of the ash. Above it for a certain distance there will be a fixed bed. We assume that minimum fluidization takes place at the level where the voidage becomes equal to 0.6, i.e., where $\eta = 0.540$. F , which will be constant throughout the column, may be calculated from the known parameters of the problem, and accordingly we can find the pressure p at the level of minimum fluidization using (15). The conditions in the fixed bed are not of great importance for the history of the ash flow. Hence we take a value of y_{mf} , the height at which fluidization begins, by assuming that the voidage averages 0.5 over this distance, and therefore, using (1) and (2), and integrating over y

$$(16) \quad y_{mf} = \frac{p_o - p}{0.5 \rho_{oo} g}$$

Density at the level of minimum fluidization can be calculated from (2) adopting a value of 0.60 for the voidage at minimum fluidization [Leva, 1959, fig. 2-6, p.21]. By the application of (1), in the form

$$(17) \quad \frac{dp}{dy} = -g\rho_s = -g(1-\epsilon) \rho_{oo}$$

we can determine the pressure at the next higher step, assuming second differences can be neglected. At the new level we can employ (15) to calculate η , and then the determination of the voidage at the next step resolves itself into the solution of the third degree equation (14).

When we consider the equations (13) - (15), it appears, at first, that the integration of ϵ in terms of y must be carried out for a range of values of F , p_o , and $\rho_{oo}g$; i.e., that a triple infinity of curves are required. It turns out, however, from (15) that once a value of F is given, the function η , and hence ϵ , depend only on p/p_o . Then if, instead of y , in (17), we use the non-dimensional variable

$$(18) \quad \bar{y} = \frac{g\rho_{oo}}{p_o} y$$

we find

$$(19) \quad \frac{d}{d\bar{y}} \left(\frac{p}{p_o} \right) = -(1-\epsilon)$$

so that the variation of p/p_0 with respect to \bar{y} is a function of ϵ only.

We can now prepare a graph (Fig. 1) showing the variation of ϵ with \bar{y} for various values of F ; on the graph can be drawn the values of p/p_0 . The computations for this graph were carried out on a 7090, and spot checked by hand computation.

To use the graph we first determine F .

- a. m will normally be 18.016 for steam.
- b. R is the gas constant, 8.317×10^7 for cgs units.
- c. T may be taken as 1123°K , according to F. R. Boyd [1961].
- d. ρ_{00} is near 2.4.
- e. $g = 162$ for moon, 980 for earth in cgs units.
- f. D_p should be taken near the lower end of the distribution of particle size, since it is the smallest particles that control the size of the passages. Say $D_p = 0.01$ cm.
- g. ϕ_s , the shape factor, may be estimated from p. 47 of Leva's book; say 0.8.
- h. $\mu = 4.0 \times 10^{-4}$ for steam at 1123° .
- i. The value of q cannot be estimated a priori: from comparison with terrestrial flows it appears that it must be in the vicinity of 10^{-7} grams of gas per gram of solid per second.

We next choose a value of p_0 . This is equal to the total static pressure exerted by the flow on its base, and can be estimated with some confidence, if the thickness of the flow is specified. With p_0 , ρ_{00} , and g in hand, we can calculate \bar{y} for any specified value of y . We enter the

graph with \bar{y} and F , and take out the values of ϵ and p/p_0 . From these we at once calculate the solids density and the gas pressure; from the latter, using (3), we obtain the gas density; and from (7) the gas velocity.

If we wish to compare phenomena on the earth with those on the moon for a given thickness (in grams per cm^2) of ash, then since p_0 is proportional to g , the ratio of y to \bar{y} will be the same in the two cases. The difference will then depend on the change in F . Hence it appears that an ash flow on the moon will be similar to one on the earth, other things being equal, if q is increased inversely as the square of the ratio of the two values of g . Since the latter ratio is $1/6.036$, it follows that the amount of gas required to fluidize an ash flow on the moon is $1/36$ of that required on the earth.

This relation was pointed out by O'Keefe and Cameron [1963]. Dr. Philip Cressy has kindly pointed out some arithmetical blunders in that paper, which caused about a factor of 10 overestimate of the steam density and hence the gas flow required for minimum fluidization and a similar underestimate of the duration and distance of the flow. In addition, a voidage of 0.2 was assumed, instead of 0.6, which would have again halved the density and gas flow, without greatly changing the duration or extent. These corrections tend to strengthen the argument of that paper, which, so far as ash flows are concerned, is a first approximation to the model presented here.

Tables 1a and 1b present a comparison of the dense phases of a terrestrial and a lunar ash flow. The constants have been so chosen in the terrestrial flow as to make the value $\epsilon = 0.8$ occur quite near a pressure of 1 atmosphere, i.e., at the ground level. The critical constant is the gas emissivity q for which we have taken 3.56×10^{-7} , which makes $F = 1$. In the lunar flow, the calculation has been made for the same total mass per square centimeter (and hence a value of p_0 about 1/6 as great). The parameter F is reduced by the factor $(g_{\text{moon}}/g_{\text{earth}})^2$ to .0274. The calculation shows that a voidage of 0.8 is reached at a pressure which is over 90% of the pressure at the base of the flow. It follows that the dilute phase will be of great importance in the lunar case.

In any case, there will be a significant dilute phase with a lunar ash flow, as may be seen by considering (7). Near the top of the flow $(p_0 - p)$ will approach some constant values. But p will tend to zero; and hence by (3), ρ will also tend to zero, so that the equation must be balanced by a marked increase of the gas velocity v . The process resembles a vacuum cleaner. As soon as v rises above the velocity of fall of the ash particles (as mentioned above) the ash begins to be carried away. In the absence of a top pressure, this will always happen; and thus the dilute phase will always play some role in a lunar ash flow; as we see from Table 1b, it may form the major part of the flow.

4. Mechanics of ash flows: the dilute phase.

In the dilute phase, it is still possible to regard the gas-dust mixture as isothermal, since the heat lost during a flow, due to all causes, is still negligible compared to the heat content. A small amount of heat is lost by the escape of the fluidizing gas; but since the total amount of gas is of the order of 1% of the rock, the loss is not very great. Some more is lost by radiation. An idea of the effectiveness of radiation cooling can be gained from the cooling of the moon's surface during the lunar night; it reaches only to depths corresponding to less than 1 gram/cm². In our case, the absolute temperature is some 4 times higher, which implies cooling which goes some 250 times faster, and would reach comparable depths in an hour or so. Cooling by conduction is less than on the moon, since the dust particles are not in contact. Cooling by convection cannot take place in a lunar flow, since the gas is evolved from the solids and therefore is at the same temperature because the isothermal case has been accepted above for the solids. In a terrestrial ash eruption of small size, the mixing of air with the volcanic gases may lead to cooling; but in such a case we have, not an ash flow, but an ash fall.

The expansion of the gas itself would tend to cool the mass; but, as noted above, the gas is only 1% at most by weight; hence cooling by expansion is also negligible.

The gas-dust cloud thus remains isothermal. It is probably turbulent, and therefore well-mixed, both because the process of liberation, by slugging, is irregular, and because the Reynolds number, R_e , given by

$$(20) \quad R_e = \frac{\rho v L}{\mu}$$

is high. For example, ρ is of the order of 10^{-2} , v , 10^2 , and μ , 10^{-3} . For L , the shortest length which it is reasonable to take is the scale-height, H , which, as we shall see, is of the order of 10^4 centimeters. Thus R_e is something like 10^7 , and the flow is expected to be turbulent.

The adiabatic law

$$(21) \quad p \propto \rho^\gamma$$

does not differ significantly from the isothermal law (Boyle's Law)

$$(22) \quad p \propto \rho$$

in our case because the exponent γ is the ratio of the specific heat of the mixture at constant pressure to its specific heat at constant volume. With a large admixture of dust, as here, the specific heat is largely that of the solid matter, which is almost completely independent of the pressure; hence γ is very nearly 1.

We may therefore calculate the scale height of the dilute phase by the law for an isothermal atmosphere. The easiest approach is to use Halley's original formulation, namely

$$(23) \quad \rho = \rho_0 e^{-(\rho_0/p_0)gy}$$

In the dilute phase, the bulk density is substantially that of the solid matter, i.e., the gas density may be neglected as usual. Then

$$(24) \quad \rho_s = (1-\epsilon)\rho_{00}$$

which, for $\epsilon = 0.95$, becomes $.125 \text{ gm/cm}^3$. The pressure, in the lunar case of Table 1b is about $550,000 \text{ dynes/cm}^2$; in the terrestrial case, Table 1a, about 1 million. The scale height, H , is thus

$$\frac{p_0}{\rho_s g}$$

We find 270 meters for the moon, and about 80 meters for the earth. The same result could be reached, though less directly, using the conventional formula

$$(25) \quad H = \frac{RT}{gm}$$

provided that we adopt a fictitious molecular weight which averages the dust particles, each as a single molecule, into the mean molecular weight, m .

The dilute phase may occur in terrestrial flows. To investigate this question, we make use of the formulas of Cook [1961] for calculating the compaction in a terrestrial ash flow. The compaction, c , is defined as the ratio of the final thickness, T_f , of the ash flow deposit (on a level or low area) to the normal thickness, T_n , possessed by the flow

while moving

$$(26) \quad T_n c = T_\ell .$$

If there is a topographic high standing at a height H above the level or low ground, the thickness of the flow while it is in motion will here be reduced to $T_n - H$; the final thickness over the high, T_h , will be given by

$$(27) \quad (T_n - H)c = T_h .$$

If T_ℓ , T_h , and H are measured, we can deduce c .

Lacroix [1904] gives a thickness, T_ℓ , of only 50 centimeters for the ash deposit at the mouth of the Riviere Blanche from the great eruption of Mont Pelée, in 1902. The total thickness, T_n , of the active region of the flow may be estimated from the fact that near St. Pierre the evidence of mechanical destruction ceased at about the 190-meter contour, and was much diminished even at 150 meters. It should be noted that the conspicuous huge clouds, discussed by Lacroix, extending several kilometers above the flow, are almost insignificant in considering its action; they were undoubtedly much more dilute than what we are here calling the dilute phase. The compaction from the above figure would be 0.003, and $1-\epsilon < 0.003$, allowing for voidage in the deposits. Thus $\epsilon > 0.997$. The estimate is unsatisfactory because the ash deposit was much less at St. Pierre than at the Rivière Blanche; on the other hand, it neglects the

ash carried out to sea and the local terrain height under the flow.

Nevertheless, it is clear that the Peléean flow was dilute.

Cook's calculations show, however, that most deposits of welded tuff involved values of c between 0.26 and 0.49, and thus correspond to the dense phase of fluidization.

In the lunar case, we would expect that a dilute flow would always form above the dense flow. Owing to its greater mobility, and the complete lack of air resistance, the dilute phase would normally go faster down-slope than the dense phase. But the dense phase would continually renew the dilute phase; any reduction in the pressure of the dilute phase would cause the velocity of gas outflow to increase again, and hence restore the dilute phase pressure. The end result might well be that the whole flow would be converted to the dilute phase.

Something of this kind may explain the topographic relations seen around the Hadley Rill (Fig. 2) described by W. S. Cameron [1964], in which the rill diminishes steadily as we go down from the source, until it vanishes. A sheet of some kind, ^(the Palus Putredinis) covers the whole region uniformly and extends downward toward Archimedes. The rill may have been eroded by the motion of the dense phase, as Mrs. Cameron has suggested; and its diminution may reflect the pseudo-evaporation by which the dense phase is converted to dilute phase. The covering sheet of mare material may be the deposit from the dilute phase.

5. Sorting in lunar ash flows.

We are now ready to take up the problem of sorting, as implied by Barnes's hypothesis. Three mechanisms should be examined.

a. Segregation. According to Leva [1959], p.107, the result of prolonged fluidization is to segregate a bed so that the smallest particles are at the top and the larger ones underneath. Cook [1961] Fig. 17-20, shows that there is a marked variation in the percentage of crystals within a given ignimbrite sheet.

b. Elutriation. This is the differential blowing away of the fine particles. It occurs, as might be expected, when the velocity of the gas flow exceeds the free-fall velocity of the particles. In the presence of a range of particle size, it is obvious that the smaller particles will go into the dilute phase before the larger ones. The significant correlations are with gas velocity and fines diameter, as would be expected. It is also clear that elutriation will be most significant in thin beds.

Numerical evaluation is, however, very unfavorable. The rate of elutriation is given, according to Leva, p.124, by

$$(28) \quad \log \frac{C}{C_0} = -k\theta$$

where C_0 is the original concentration of fines, C the final concentration, θ the time, and k a constant. Significant elutriation requires $k\theta$ at the order of 1. Leva gives (p.128)

$$(29) \quad k = 1.0 \left(\frac{U_f - U_t}{U_t} \right)^{1.3} \frac{D_b^{0.7}}{L_{mf}^{1.4}}$$

where D_b is the diameter of the particles in the bed in inches, L_{mf} is the height of the bed in feet, k is in inverse minutes, U_f is the fluid velocity, and U_t the terminal velocity of the particles in the fluid at rest.

The maximum value of the parenthesis is of the order of 1; for $D_b = 2.5 \times 10^{-3}$, and $L = 10^2$, it is clear that k will be less than 10^{-4} minutes, so that elutriation will require hundreds of hours. Thus elutriation is not likely to play a significant role in a dense, thick bed.

c. Thirdly, we may consider sorting in the dilute flow. Though no industrial formulae are available, it is clear that in spite of turbulence there will be a tendency for the largest particles to settle out first, and the smaller ones afterward, just as in terrestrial aeolian deposits, which also sort in spite of aerodynamic turbulence. It is highly probable that the ash deposited from the dilute phase of a lunar ash flow is sorted by size, partly as a result of segregation in the dense phase, partly as a result of elutriation, but especially as a result of differential settling rates.

6. Conclusions

a. Since the magma from which the ash flow comes may well have been more acid than terrestrial magmas [Walter, 1964], it is reasonable to suppose that the crystals would be predominantly quartz. Then sorting by size in a dilute flow, as described above, will explain the tendency to which Taylor and others have drawn attention, for the silica content

of tektites to vary from specimen to specimen, independently of the other constituents, while almost all the others vary together.

b. This process, carried to extremes, could produce the Darwin glass or the Libyan desert glass.

c. Fine particles, deposited at a temperature of the order of 1120°K in a hard vacuum as described here would lose their volatiles rapidly. Hence we can understand the low content of water and other volatiles in tektites. It is this characteristic which makes it possible to form dense glasses from them, and so distinguishes them from nearly all natural terrestrial materials.

d. The compact structure may be the result of welding by collapse of the porosity, as in a terrestrial welded tuff.

e. Material deposited from the dilute phase would be bedded, like terrestrial aeolian deposits; it might, therefore, resemble the Muong Nong material, especially if flow had taken place after deposition and even welding. Flow would be expected because the effective insulation of the hard vacuum on the moon would keep the material hot for a long time. Flow is a function of viscosity and time; the viscosity might not be much greater than in terrestrial flows, but the time would be much greater. Some ash flow tuffs show evident traces of flow.

f. The lack of scarps around the maria accords with what would be expected.

g. The "fairy-castle structures" which Hapke has invoked to explain the lunar photometric function were produced by him in the laboratory

by permitting particles to settle out of a gas, i.e., in the same manner as here contemplated. It is evident that the surfaces of the maria can be explained this way.

It is puzzling that the highlands should resemble the maria so closely in their photometric properties. Note that the scale-height of the cloud depends on the ratio of dust to gas. It will increase as the dust falls out toward a limiting value of about 800 kilometers. At this height the mean free path would certainly greatly exceed the diameter of the ash particles, so that they would no longer be supported. The limiting density is about 10^{-6} gm/cm³; with this density and a scale height of 10 km, dust might be deposited on the tops of the highest mountains. The required surface density of water is 1 gm/cm³, or a total of 380 km³; a very large terrestrial ash flow may liberate a comparable volume of water. Hence the lunar highlands may be covered with a very thin coating of the same material found in the maria.

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REFERENCES

- Adams, E. W., Aerodynamic analysis of tektites and their parent bodies,
Ch. 7 in Tektites, edited by J. A. O'Keefe, University of Chicago
Press, Chicago, 1963.
- Barnes, V. E., Tektites, GeoTimes, 1, 6, 7, 16, 1956.
- Barnes, V. E., University of Texas Publication 3945, 477-656, 1939.
- Boyd, F. R., Rhyolite plateau, Yellowstone Park, Wyoming, Geol. Soc. Am.
Bull., 72, 387-426, 1961.
- Cameron, W. S., An interpretation of Schröter's Valley and other lunar
sinuous rills, J. Geophys. Res., 69, 2423-2430, 1964.
- Chapman, D. R., and H. K. Larson, On the lunar origin of tektites,
J. Geophys. Res., 68 (14), 4305-4358, 1963.
- Cherry, R. D., and S. R. Taylor, Studies of tektite composition--II,
Geochim. et Cosmochim. Acta, 22, 164-168, 1961.
- Cherry, R. D., S. R. Taylor and M. Sachs, Major element relationships in
tektites, Nature, 187, 680, 681, 1960.
- Cook, E. F., Stratigraphy of tertiary rocks in eastern Nevada,
Preprint, University of Idaho, 1961.
Monthly Notices of the Royal Astronomical Society,
Gold, T., The lunar surface, 115, 585-604, 1955.
- Greenacre, J. A., A recent observation of lunar color phenomena, Sky and
Telescope, 26, 316, 317, 1963.
- Griggs, R. F., Our greatest national monument, National Geographic, 40,
219-292, 1921.
- Hapke, B. W. and H. Van Horn, Photometric studies of complex surfaces
with applications to the moon, J. Geophys. Res., 68, 4545-4570,
1963.

Kozyrev, N., Volcanic phenomena on the moon, Nature, 198, 979, 1963.

Lacroix, A., La montagne Pelée et ses eruptions, Masson et Cie.,
Paris, 1904.

Lamb, H., Hydrodynamics, 5th edition, Cambridge Univ. Press, 1924.

Leva, M., Fluidization, McGraw-Hill, New York, 1959.

Loewinson-Lessing, F., Comptes rendus, Acad. Sci. U.S.S.R., new series,
3, 181-185, 1935.

Mueller, F. P., Tektites from British Borneo, Geol. Mag., Decade VI,
2, Jan.-Dec., 1915.

O'Keefe, J. A., Tektites as natural earth satellites, Science, 133,
562-566, 1961.

O'Keefe, J. A., Tektites and impact fragments from the moon, Sci. Am.,
210, 50-57, 1964.

O'Keefe, J. A., and W. S. Cameron, Evidence from the moon's surface
features for the production of lunar granites, Icarus, 1,
271-285, 1962.

O'Keefe, J. A., and B. Shute, Tektites and natural satellites of the earth,
Aerospace Engineering, 20, 26, 27, 65, 66, 1961.

Pettijohn, F. J., The Sedimentary Rocks, Harper and Bros., New York,
1957.

Schnetzler, C. C., and W. J. Pinson, Jr., The chemical composition of
tektites, Ch. 8 in Tektites, edited by J. A. O'Keefe, University
of Chicago Press, Chicago, 1963.

Taylor, S. R., and M. Sachs, Geochemical evidence for the origin of
australites, Geochim. et Cosmochim. Acta, 28, 235-264, 1964.

- Taylor, S. R., and M. Sachs, Abundance and distribution of alkali elements in Victorian australites, Geochim. et Cosmochim. Acta, 25, 223-228, 1962.
- Taylor, S. R., M. Sachs, and R. D. Cherry, Studies of tektite composition-I, Geochim. et Cosmochim. Acta, 22, 155-163, 1961.
- Taylor, S. R., and M. Solomon, The geochemistry of Darwin glass, Geochim. et Cosmochim. Acta, 28, 471-494, 1964.
- Tilton, G. R., Isotopic composition of lead from tektites, Geochim. et Cosmochim. Acta, 14, 323, 1958.
- Tisserand, F., Traité de Mécanique Céleste, Gauthier-Villars et Fils, Paris, 1896.
- Urey, H. C., The early history of the solar system as indicated by the meteorites, Proc. Chem. Soc., (no vol. number) 67-78, 1958.
- Urey, H. C., Origin of tektites, Nature, 179, 556-557, 1957.
- Walter, L. S., Lunar differentiation processes, Submitted to New York Academy of Sciences for inclusion in monograph, Geological Problems in Lunar Research, 1964.
- Viste, E., and E. Anders, Cosmic ray exposure history of tektites, Enrico Fermi Institute Preprint, 61-66, J. Geophys. Res., 67, 2913, 1962.

Table 1 a

Terrestrial Case

Height (cm)	Voidage	Pressure (dynes/cm ²)	Gas Density (gm/cm ³)	Gas Velocity (cm/sec)	Solids Density (gm/cm ³)
0	0.50	3.56×10^6	-	0	1.20

----- Fixed Bed -----

1062	0.60	2.31×10^6	4.46×10^{-4}	1.22	0.96
1500	0.66	1.93	3.72	1.59	0.82
2000	0.72	1.56	3.00	2.42	0.68
2500	0.76	1.25	2.40	3.50	0.57
2972	0.80	1.00	1.93	4.82	0.48

----- Atmosphere -----

Table 1 b

Lunar Case

Height (cm)	Voidage	Pressure (dynes/cm ²)	Gas Density (gm/cm ³)	Gas Velocity (cm/sec)	Solids Density (gm/cm ³)
0	0.50	0.59×10^6	-	0	1.20

----- Fixed Bed -----

44	0.60	0.58×10^6	1.12×10^{-4}	0.19	0.96
100	0.69	0.57	1.11	0.33	0.75
200	0.76	0.56	1.09	0.56	0.58
300	0.79	0.55	1.07	0.76	0.50
330	0.80	0.55	1.06	0.81	0.48

----- Dilute Phase -----

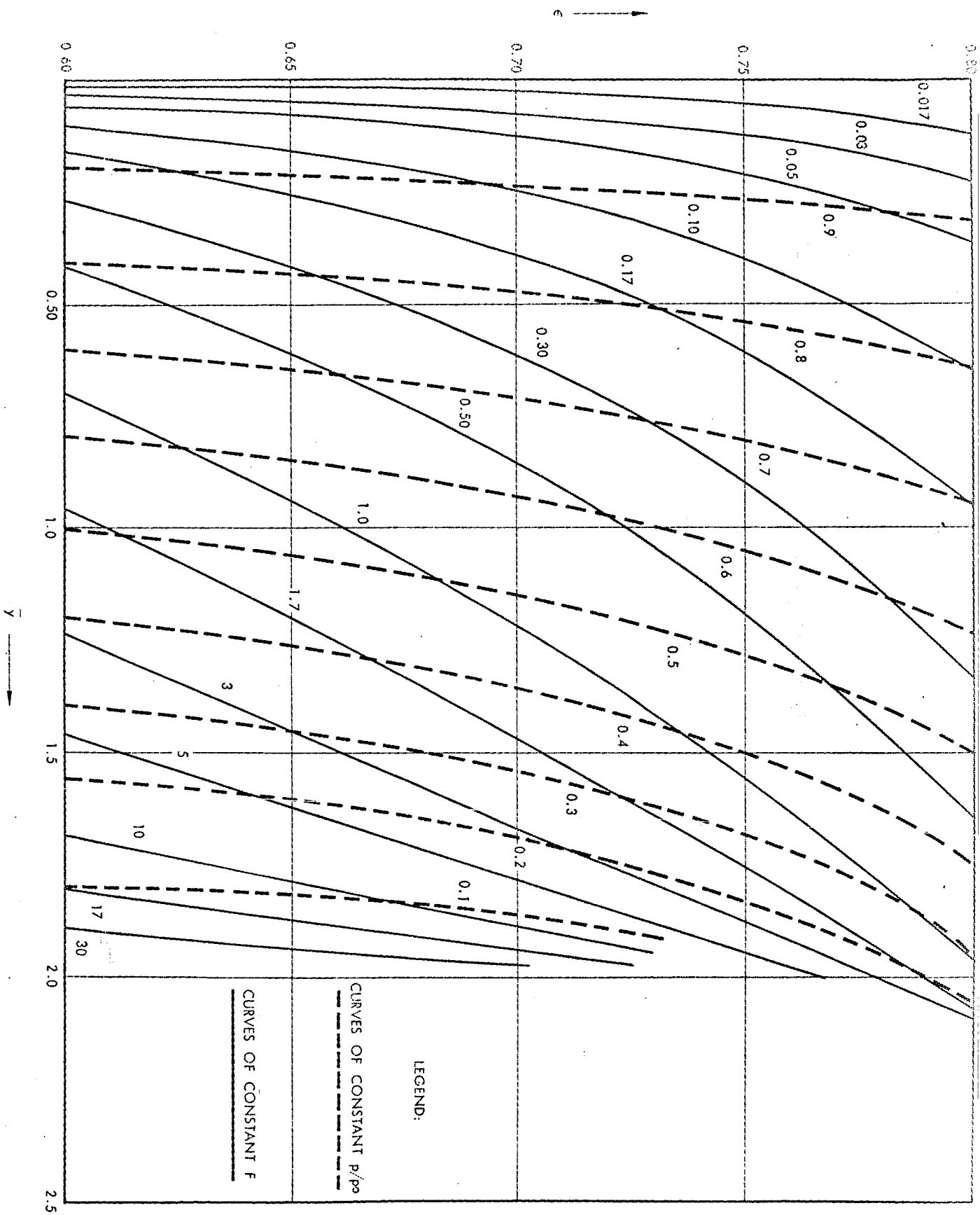


Fig. 1 Pressure ratio, p/p_0 , and voidage ϵ , as a function of the non-dimensional height y , for varying values of the parameter F , in the dense phase of ash flows